ELECTROMAGNETIC COMPATIBILITY STUDY OF CONDUCTING WIRES

Levent Uluc

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THESIS

ELECTROMAGNETIC COMPATIBILITY STUDY
OF CONDUCTING WIRES

by

Levent Uluc

December 1974

Thesis Advisor: R. W. Adler

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Prepared for:
Naval Surface Weapons Center
Dahlgren, Virginia

T164

NAVAL POSTGRADUATE SCHOOL
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This thesis prepared in conjunction with research supported in part by Naval Surface Weapons Center, Dahlgren, Virginia.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NPS-52AB74121	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Electromagnetic Compatibility Study of Conducting Wires		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1974 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Levent Uluc in conjunction with Professor R. W. Adler		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE December 1974 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Wires
Electromagnetic
Compatible

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(Page 1) S/N 0102-014-6601

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Electromagnetic Compatibility Study

of Conducting Wires

by

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Lieutenant Junior Grade, Turkish Navy
B.S., Naval Postgraduate School, 1974

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1974

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Assigning probabilities to RF power picked up on aerospace cables at microwave frequencies by using analytical methods was the objective of this thesis. The coupling from radiated fields to typical unshielded wires was calculated in the frequency range 1 GHz to 10 GHz by utilizing a thin wire antenna computer program. The data obtained from the calculations were used to get the cumulative distribution function of absorbed power and also to observe its variation with changing frequency and loading of the wires.

The results of this analysis compared favorably with those of a previous experimental approach. This demonstrates that analytical methods can be utilized for calculating and predicting the coupling from radiated fields to unshielded wires.

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ACKNOWLEDGEMENT

The author wishes to express his appreciation to Professor R. W. Adler of the Naval Postgraduate School, Monterey, California, for the invaluable aid and counsel which he has offered during the preparation of this thesis, and to Mr. Ronald Prehoda of the Naval Weapons Laboratory, Dahlgren, Virginia, whose interest and support alleviated the solution of many problems that arose during this study.

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I. INTRODUCTION

A. NEED FOR THE STUDY

In designing aerospace electronic systems to operate in high level radiated environments, the susceptibility of electro-explosive devices, transistors and integrated circuits to microwave power picked up by connecting cables has long been recognized as a serious problem. Investigations into the susceptibility of semiconductor components have shown that they respond to microwave energy at power levels of less than a milliwatt. With ever increasing radiated environment levels the pickup phenomenon and the protection afforded by cable shields have become more important.

In a radiated environment, circuit wiring can frequently be as efficient as tuned dipole antennas. This provides much more than a few milliwatts of power to cable terminations when wiring is exposed to high radiated environments.

Designing aerospace electronic systems to survive and operate in high power radiated environments requires techniques for predicting and evaluating the coupling from radiated fields to susceptible components. This permits system designers to establish the overall required system protection.

B. STATEMENT OF THE PROBLEM

Inefficiently shielded aerospace cables may pick up enough energy to cause the electro-explosive devices of a missile to prefire or the missile to change its course. Even with good shielding, pickup sufficient for detonation can occur in a severe environment.

Therefore in missile design, for successful operation in hostile environments, protection of electronic circuits against high power radiated fields must be provided.

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The necessity of evaluation and prediction of RF coupling to permit system designers to establish the overall required system protection was the driving force for this thesis.

C. PREVIOUS WORK

In an electronic circuitry, a cable can be thought of as an antenna which couples power from the radiated field to the sensitive component and an effective aperture can be used to describe the coupling problem.

McDonnell Douglas Astronautics Company - East (MDAC-E) has worked on solving the high frequency cable coupling problem, and published the results of its studies as a report[1]. According to this report the studies have resulted in an approach which divides the problem into two parts: (1) effective aperture of the unshielded cable and (2) shielding effectiveness of the cable shield. These can be stated in equation form:

$$P_r(W) = P_D\ (W/m^2) \times A_e\ (m^2) \times SE$$

where: P_r = power received by cable termination

P_D = power density of radiated field

A_e = effective aperture of unshielded cable

SE = shielding effectiveness of cable shield

MIL-STD-1377 (NAVY) provides a good method to evaluate shielding parameters independent of other variables (polarization, aspect angle, cable length, etc.). Due to the complexity of practical shielding and enclosure discontinuities, shielding effectiveness is determined by empircal methods in this approach. However, for determining the effective aperture in MDAC-E approach both analytical and experimental methods may be utilized.

To validate both the MDAC-E approach and the MIL-STD-1377 shielding effectiveness measurement technique, data have been processed from a large

number of anechoic chamber measurements of RF pickup at 3.0 GHz and 9.1 GHz for shielded and unshielded twisted wire pairs. The cumulative distribution of RF pickup for each test configuration has been calculated. The data were put in a form suitable for assigning probabilities. Results of this work showed that the MDAC-E approach is valid and that MIL-STD-1377 provides an accurate method to measure shielding effectiveness. The data also indicated that the maximum effective aperture of an electrically long unshielded twisted wire pair can be approximated by a half-wave dipole at microwave frequencies. It was found that the unshielded cables had a measured maximum effective aperture very close to that calculated using a half-wave dipole model.

In statistical analysis of MDAC-E approach an antenna pattern of received power was plotted while the cable was exposed to a plane wave in an anechoic chamber and rotated 360 degrees in azimuth. A separate pattern was recorded every 5 degrees in evaluation, from 0 through 180 degrees.

Using these data the cumulative distribution of RF pickup was obtained. Figure I-1 shows the cumulative distribution of the data points for 9.1 GHz and the 360 degree shielded cable and the unshielded cable which had the same terminating impedances. The two curves are very nearly equidistant to all points. If one could measure or calculate the coupling to an unshielded cable, then shield termination techniques can be evaluated using MIL-STD-1377, and RF coupling to the shielded cable can be predicted.

However a point-to-point corresponding reduction in RF coupling does not exist. That is, the antenna patterns for the shielded and unshielded case are not similar in a geometrical sense. In actual use, the cable will be placed in proximity to objects which will change the RF coupling for a particular aspect angle considerably, but the statistical distribution will

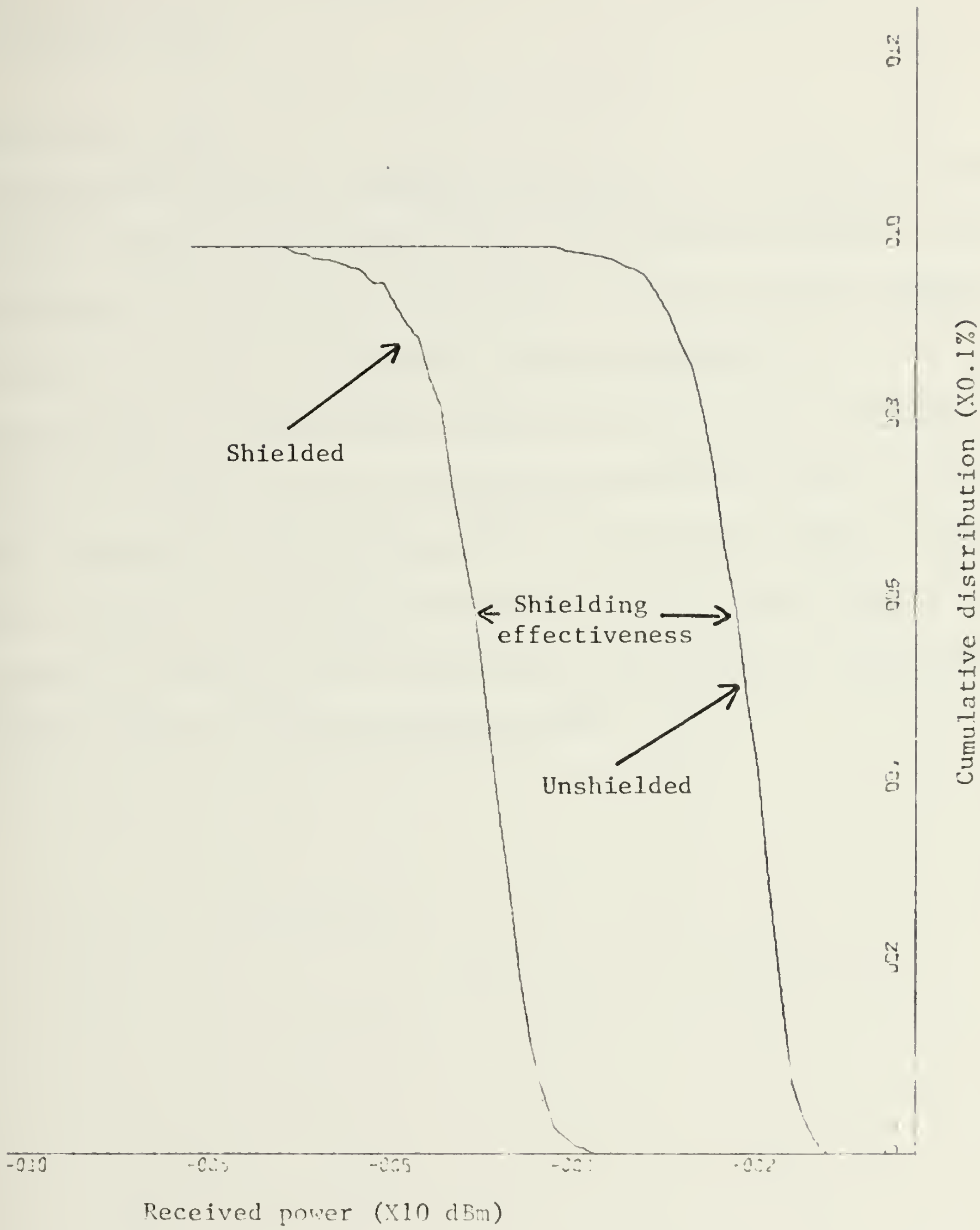

Figure I-1

Comparison of distribution of received power for shielded and unshielded cable. Field intensity=1 V/m

not change. Therefore, RF coupling to the shielded cable must be predicted on a statistical basis.

D. SCOPE OF THE STUDY

In this thesis study the cumulative distribution of RF pickup of unshielded wires was evaluated by utilizing completely analytical methods. Since unshielded wires can be thought of as antennas, antenna modeling programs can be used to calculate the RF power pickup by computers.

M B Associates Antenna Modeling Program (AMP) was used to calculate the currents on a straight wire in a free space radiated environment. The magnitudes of currents for different aspect and polarization angles provided the data to compute the cumulative distribution of RF pickup energy. For the purpose of computing the RF power pickup and plotting the cumulative distribution another computer program was used.

II. ANALYSIS AND PROGRAMS

A. MODEL OF STRUCTURE AND STATISTICAL ANALYSIS

The test structure used by MDAC-E was a model of an integrated circuit NAND gate driving another NAND gate through a twisted wire pair exposed to a microwave field. The IC impedances were measured and simulated using impedance matching networks so that a receiver with large dynamic range could be used to monitor power received by the termination. The test cables were a pair of twisted wires, one twist per inch, 23-5/8 inches long. One conductor was connected to the center pin of type N to type BNC adapter at each end. The other conductor was soldered to the connector shells. With this test structure several sets of measurements were made for different configurations, three of these configurations are shown in Table II-1.

CONFIGU-RATION	FREQUENCY	LOADS	
		TERMINATION	CALCULATION AT
1	9.1 GHz	45+j75	110+j130
2	3.0 GHz	40-j23	24-j28
3	1.0 GHz	50	50

Table II-1: Configuration record

In this study, the test structure explained above was simulated to calculate RF pickup power and its cumulative distribution calculated by computer programs. In order to be able to compare these results with those of MDAC-E,

all the parameters of the model of the test structure were chosen to be the same as MDAC-E's parameters shown in Table II-1.

The test structure which consisted of a pair of twisted wires and two loads connected to their ends was modeled by a single wire having one load at each end. Since one of the wires in the test structure was used as ground cable, the current produced by incident plane waves on this cable flowed to ground and made no contribution to the amount of power picked up by the terminating impedance. Therefore the ground cable of the test structure was omitted in the model.

The 23-5/8 inch length of the model wire was kept constant and several positions of the loads were tried for optimum correlation with MDAC-E's result. It was found that the best location for the loads was the ends of the wire, as it was in the real case. These positions of the loads gave the optimum correlation for both configuration 1 and configuration 2. The comparison for configuration 3 was not done, since the cumulative distribution of RF pickup power obtained by MDAC-E was not available.

Varying the load positions demonstrated that the RF pickup power was strongly dependent on the load positions of the structure. The effect of load position on the cumulative distribution of RF pickup power is shown in Figure II-1 for configuration 2. The plotted distribution curves are for positions at 0.05 wave length and 0.15 wavelength from the ends. Variation of load locations of 0.1 wavelength caused the cumulative distribution to shift about 4 dBm. However further study showed that the amount of shifting was not directly proportional to the variation in load positions but it could fluctuate randomly between 10 and 2 dBm.

The model of the test structure in three-dimensional coordinate system is shown in Figure II-2. Load Z_2 was used as termination and power and cumulative distribution calculations were made for Z_1.

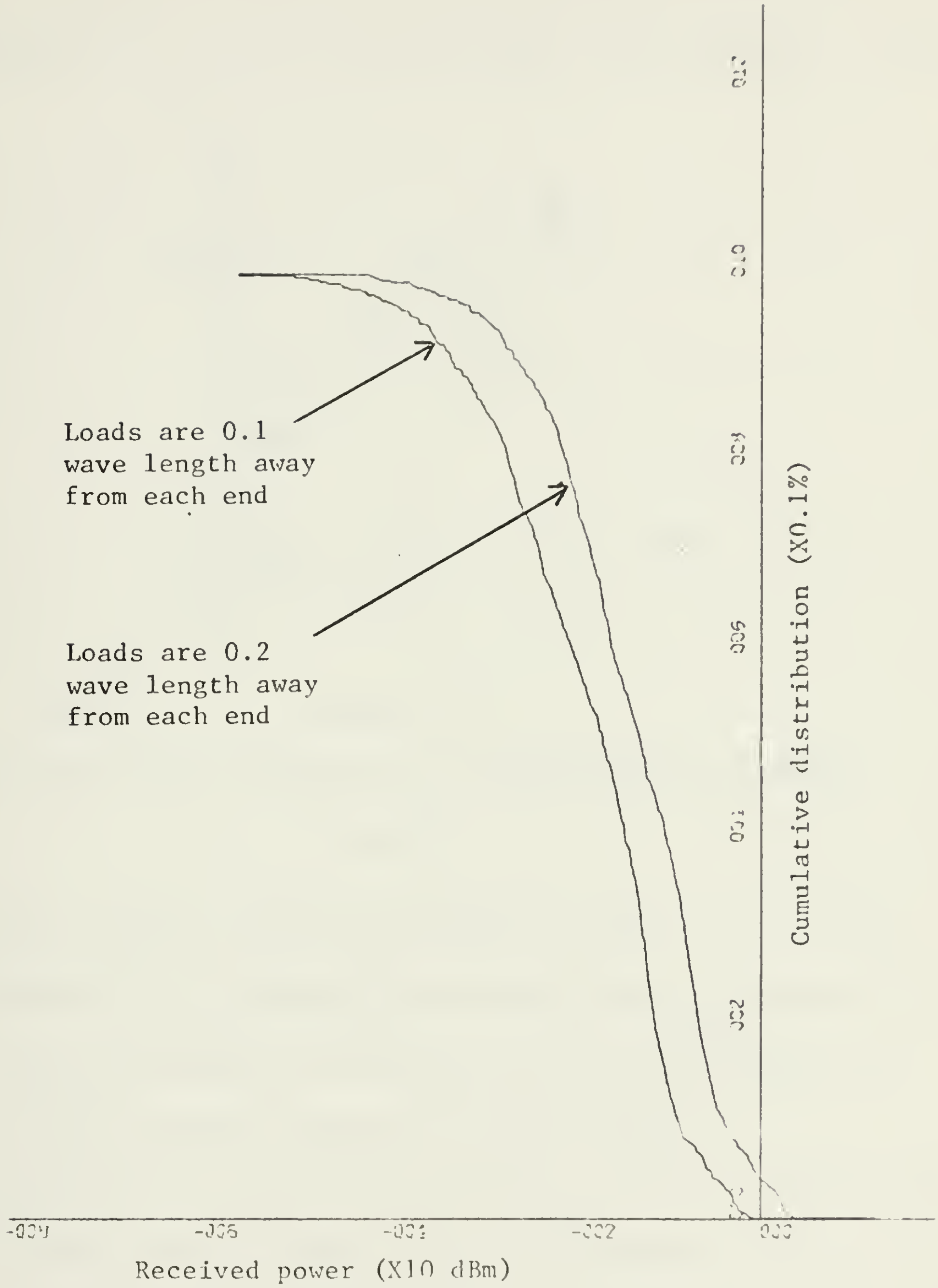

Figure II-1

Variation of cumulative distribution with varying load positions

In the statistical analysis, the first step was calculation of currents at load Z_1 for incoming plane waves which had different aspect and polarization angles(η).This was done by utilizing MBA's Antenna Modeling Program.

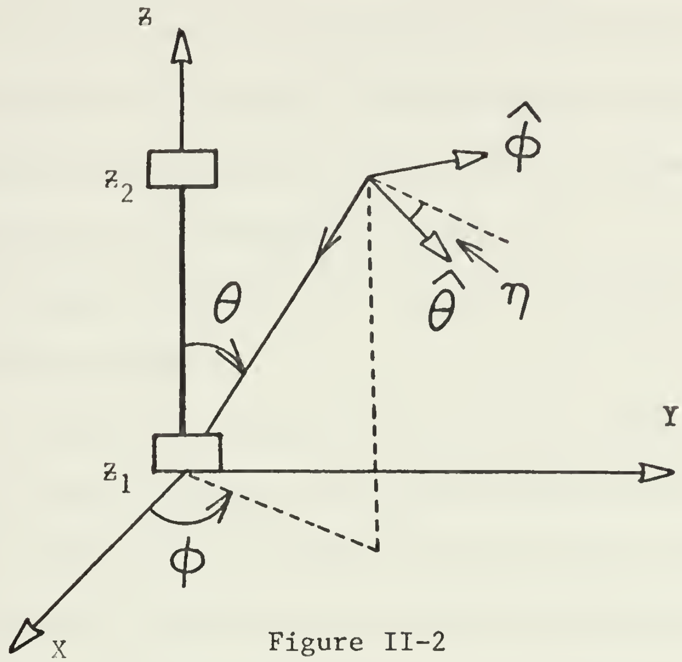

Figure II-2

Model of the test structure in three-dimensional coordinate system.

The elevation incidence angle and polarization angle were varied in 5-degree increments in calculating the spherical receiving pattern of the structure. Since the structure was symmetrical in the $\hat{\phi}$ direction, the aximuth angle (ϕ) of incident plane wave was kept constant.

To determine symmetry of polarization angles, currents were evaluated by varying both theta and eta angles from 0 to 180 degrees. It was found that incident plane waves having polarization angles between 0 and 90 degrees produced the same currents in magnitude as the plane waves having polarization angles between 90 and 180 degrees, but their phases were 180 degrees different. Therefore the eta angle scanned only 0 to 90 degrees. Since the model of structure was unsymmetrical in the $\hat{\theta}$ direction, a 180 degree sector of θ angle was covered.

B. CALCULATIONS

Calculations made to obtain the cumulative distribution of RF pickup power can be analyzed in two groups: (1) evaluation of currents at load Z_1 produced by incoming plane waves and (2) evaluation of power in dBm, calculation and plotting of the cumulative distribution.

Two separate computer programs were utilized to achieve the two groups of calculations stated above.

Evaluation of currents at load Z_1 was done by the AMP program. It is based on the thin wire electric field integral equation which relates the exciting electric field to the induced currents on some specified thin wire geometry. The integral equation is reduced to an N-dimensional system of linear equations by representing the current in terms of N sinusoidal basis functions and enforcing the integral equation at N discrete points. The unknown current vector is related to the excitation vector by a coefficient matrix which essentially depends only on the geometry of the structure. The unknown currents in the matrix equation are solved for by using the Gaus-Doolittle elimination procedure. Fields patterns can be calculated by summing the contributions of the N currents. The basic elements of the program used for solving the electromagnetic characteristics of a structure from the electric field integral equation are relatively simple. However, the existence of impedance loading, ground effects, and network options in the program increases its complexity.

Another computer program was written to calculate the RF pickup power in dBm and its cumulative distribution. It utilizes subroutine DRAWP to plot the cumulative distribution of RF pickup power.

Since it was impossible to indicate the zero power point on the dBm scale, all zero magnitude currents were extracted from the data. Hence the number of data points were reduced from 703 to 630. It was assumed that the probability of having each RF pickup power value from 630 possible values was equal. In order to calculate cumulative probabilities, the number of RF pickup power values which were greater than some certain specified level was counted and divided by 630. The Antenna Modeling Program calculates the currents on a structure for an incidence electric field of 1 V/m. In MDAC-E method, measurements have been made for an electric field of 19.4 V/m. To be able to compare the results of this study with MDAC-E's results, current magnitudes were multiplied by 19.4 to give the current magnitudes for an electric field of 19.4 V/m. The program and its flow chart are shown in Appendix A.

III. RESULTS OF CALCULATIONS

The cumulative distributions of RF pickup power for the first and second configurations in Table II-1 are shown in Figure III-1 and Figure III-2. In order to compare the results of MDAC-E's experimental approach and the computational method employed in this study, they were plotted on the same coordinate system. In both figures, it can be observed that there is a good correlation between experimental and analytical curves around the 50% cumulative probability point. However the difference between two curves increases towards the high and low power ends. This deviation of analytically obtained curve from MDAC-E's curve was caused by the differences between the actual test structure and the model of it. These differences could be divided into two groups:

1. In the test structure the two loads were connected to the ends of twisted wire pairs. But, because of the limitations of Antenna Modeling Program it was impossible to place the loads at the end points of the structure model. AMP makes its calculations assuming loads are at the center of segments. This situation causes a small part of the wire to appear after the load at the ends of the structure model. Since the current magnitudes diminish towards the end of structure, the measured values of power were smaller than the calculated values due to the larger distances of loads of structure model from ends. This phenomenon affected high power end of the analytically-obtained cumulative distribution and caused it to have larger values than the experimentally-obtained curve.

2. In order to model the test structure, solid wire was used instead of twisted wire. Since the effective cross-section area of twisted wires is

Figure III-1

Comparison of experimentally and analytically obtained cumulative distribution curves for configuration 1

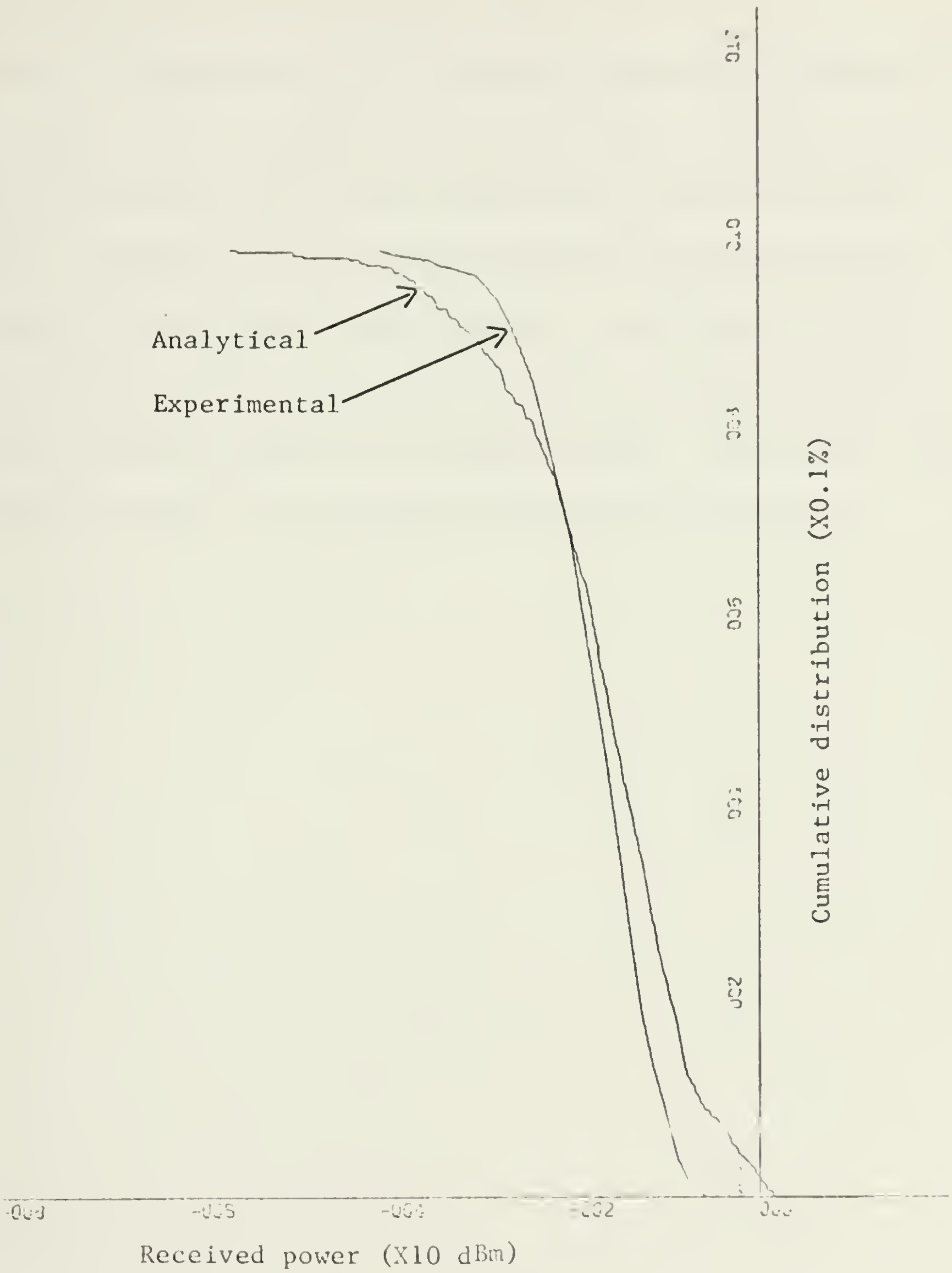

Figure III-2

Comparison of experimentally and analytically obtained cumulative distribution curves for configuration 2

larger than solid at radio frequencies, this also caused a small amount of difference between the two distribution curves.

The cumulative distribution of RF coupling for the third configuration is shown in Figure III-3. Comparing the three plots, it can be seen that the shape of distribution curves were indepndent of parameters used. However there was a shifting in the negative direction and an increase in the slope of the curves with increasing frequency. The frequency of the radiated environment and the positions of the loads on the structure were the major factors which change the amount of RF coupled energy. The values of the impedances didn't change the cumulative distribution appreciably.

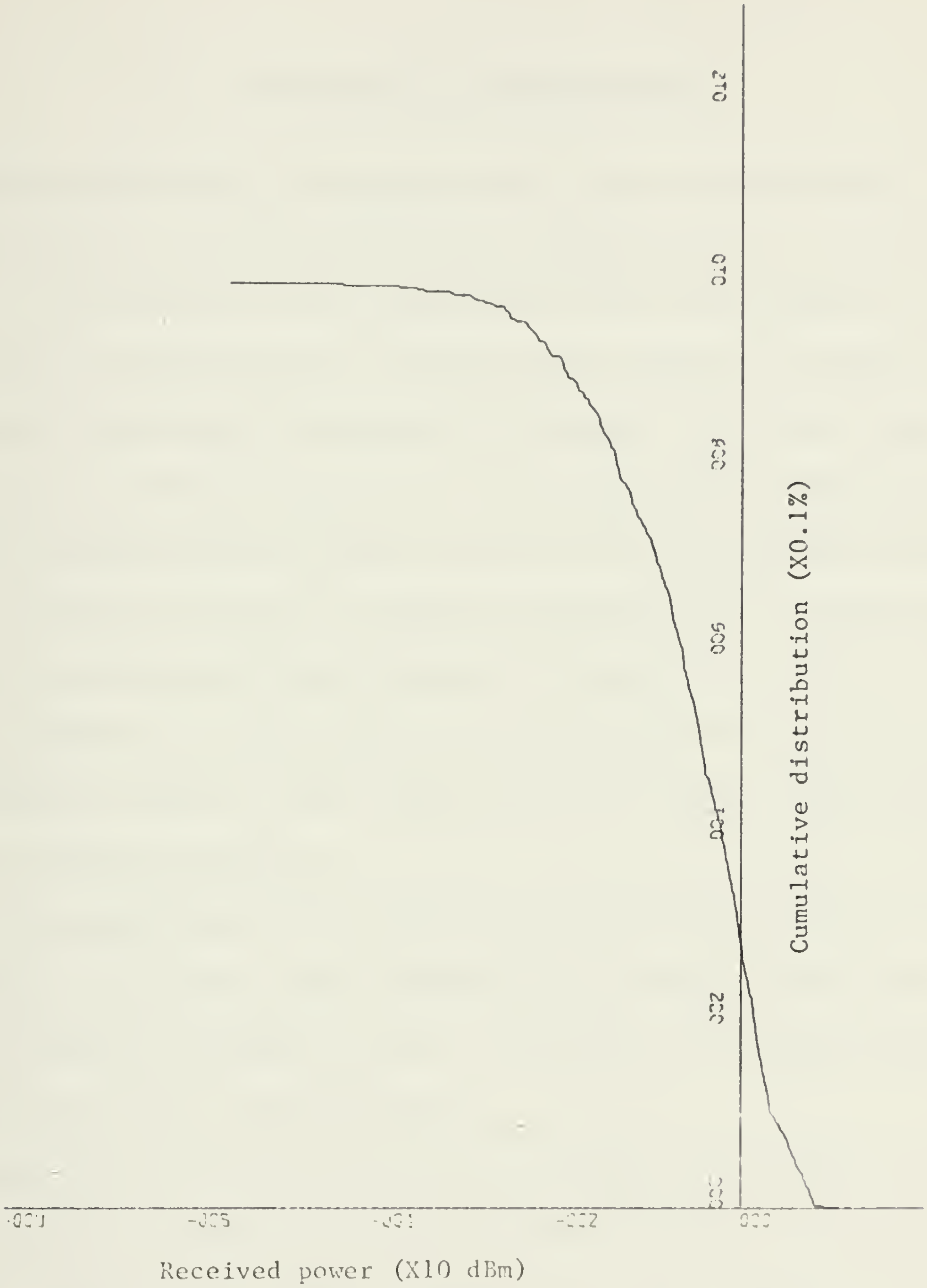

Figure III-3

Cumulative distribution for configuration 3.

IV. CONCLUSIONS AND RECOMMENDATIONS

Assigning probabilities to RF power coupled from radiated fields to aerospace cables by utilizing computational techniques was the purpose of this thesis. This objective was accomplished by use of two computer programs. A test structure which was used previously by MDAC-E to obtain the same objective experimentally was modeled to calculate the current magnitudes produced by incident plane waves. Current magnitudes calculated by use of MBA's Antenna Modeling Program provided the data for another computer program to calculate and plot the cumulative distribution of RF pickup power.

In modeling, choosing the load positions of the structure model the same as the load positions of the structure to be modeled gave the best correlation with MDAC-E's result. Also a single wire was utilized to model the two wire pair of the test structure.

The results showed that the frequency of the radiated environment and the positions of the loads on the structure were the major factors which affected the amount of coupled RF power. The effect of the other parameters on coupled RF power was relatively small.

Comparisons of the resulting curves of this study and MDAC-E's experimental approach was made and it was found that there was good correlation between them. Around the 50% cumulative probability point, agreement between the two distribution curves was even better. That is, evaluation and prediction of RF coupling from radiated fields to aerospace cables can also be done by utilizing computational techniques, which are less time consuming. Many types of wiring found in aerospace electronic circuitry can be modeled by

these computational techniques. Knowing the coupling to unshielded cables, the MIL-STD-1377 (NAVY) method of measuring the shielding effectiveness of shielded wires can be used to accurately predict RF coupling from a radiated field to the terminating impedance of shielded cables.

In practice, there is more than one subsystem which is suceptible to a radiated environment. The probability that at least one of the subsystems is vulnerable increases with the complexity of a system. For a more realistic prediction of RF coupled power to aerospace electronic systems, the variation of cumulative distribution of RF pickup power with the number of subsystems should be determined. This may be an area of possible improvement of analytical methods utilized in this study to permit system designers to predict the overall system protection.

Another consideration is to calculate the probabilities of malfunction and burnout of the susceptible components of aerospace electronic systems as a function of distance from a representative high power transmitter or as a function of the power level of a radiated environment. This is looking at the same problem from another point of view and may be an alternative computational solution.

APPENDIX A: COMPUTER PROGRAM TO CALCULATE AND PLOT

CUMULATIVE DISTRIBUTION OF RF PICKUP POWER

```
      DIMENSION CURENT(630),PCWR(630),POWRM(630),CBM(630)
      DIMENSION CELDB(340),PRCB(340),URENT(630)
      INTEGER*4  ITB(12)/12*0/
      REAL*4     RTB(28)/28*0.0/
      ITB(3)=5
      ITB(4)=7
      RTB(1)=20.0
      RTB(2)=0.2
      RL=50.0
      CKCL=630.0
      KCL=630
      WRITE (6,11)
   11 FCRMAT('1',48X,'POWER  IN  UNITS  OF  DBM')
      WRITE(6,13)
   13 FCRMAT('   ')
C     CURRENT MAGNITUDES ARE READ
      READ(5,35) (URENT(I),I=1,KOL)
   35 FCRMAT(7(1X,D10.4))
C     THIS LOOP CALCULATES THE POWER IN UNITS OF CBM
      DC 1 I=1,KOL
      CURENT(I)=19.409644*URENT(I)
      PCWR(I)=RL*(CURENT(I)**2)
C     POWER IS CONVERTED FROM UNITS OF WATS TO MILLIWATS
      PCWRM(I)=PCWR(I)*1000.0
    1 DBM(I)=10.0*(ALOG10(POWRM(I)))
C     PCWERS ARE WRITTEN IN UNITS OF DBM
      WRITE(6,56) (DBM(I),I=1,KOL)
   56 FCRMAT(8(4X,E11.5))
      DELDB(1)=12.0
      WRITE (6,12)
   12 FCRMAT('1',48X,'CUMULATIVE   PROBABILITIES')
      WRITE(6,13)
C     THIS LOOP CALCULATES THE CUMULATIVE PROBABILITIES
      DC 7 K=1,340
      CONTER=0.0
      DO 2 I=1,KOL
    2 IF(DBM(I).GE.DELDB(K)) CONTER=CONTER+1.0
      PRCB(K)=CONTER/CKOL
      IF(K.EQ.340) GO TO 7
      DELDB(K+1)=DELDB(K)-0.2
    7 CONTINUE
C     CUMULATIVE PROBABILITIES ARE WRITTEN
      WRITE(6,55) (PROB(K),K=1,340)
   55 FCRMAT(8(4X,E11.5))
      ITB(1)=0
C     CUMULATIVE PROBABILITY VS. POWER IS PLOTTED
      CALL DRAWP(340,DELDB,PROB,ITB,RTB)
      STOP
      END
```

Flow chart of the program which calculates and plots the

cumulative distribuιιon οι κr pickup power

```
        DIMENSION CURENT(630),POWR(630),POWRM(630),DBM(630)
        DIMENSION DELDB(340),PROB(340),URENT(630)
        INTEGER*4 ITB(12)/12*0/
        REAL*4     RTB(28)/28*0.0/
                  |
        -----------------------------------------
        | ITB(3) =5                             |
        | ITB(4) =7                             |
        | RTB(1) =20.0                          |
        | RTB(2) =0.2                           |
        | RL    =50.0                           |
        | CKOL  =630.0                          |
        | KOL   =630                            |
        -----------------------------------------
                  |
      ***WRITE (6,11)
 11     FORMAT('1',48X,'POWER  IN  UNITS  OF  DBM')
      ***WRITE(6,13)
 13     FORMAT('   ')
     CURRENT MAGNITUDES ARE READ

      ***READ(5,35) (URENT(I),I=1,KOL)
 35     FORMAT(7(1X,D10.4))
     THIS LOOP CALCULATES THE POWER IN UNITS OF DBM
                  |
            +------------+
           + DO          +
 +++++++++     1          +
 +         + I=1,KOL     +
 +          +------------+
 +                |
 +                |
 +      -----------------------------------------
 +      | CURENT(I) =19.409644*URENT(I)         |
 +      | POWR(I) =RL*(CURENT(I)**2)            |
 +      -----------------------------------------
 +                |
 +
 +   POWER IS CONVERTED FROM UNITS OF WATS TO MILLIWATS
 +
 +                |
 +      -----------------------------------------
 +      | POWRM(I) =PCWR(I)*1000.0              |
 +      -----------------------------------------
 +                |
 +      -----------------------------------------
1 ++++++++| DBM(I) =10.0*(ALOG10(POWRM(I)))     |
        -----------------------------------------
```

```
                          |
      POWERS ARE WRITTEN IN UNITS OF DBM

       ***WRITE(6,56) (DBM(I),I=1,KOL)
56          FORMAT(8(4X,E11.5))
                          |
            ------------------------------------------
            | DELDB(1) =12.0                          |
            ------------------------------------------
                          |
                          |
       ***WRITE (6,12)
12          FORMAT('1',48X,'CUMULATIVE   PROBABILITIES')
       ***WRITE(6,13)
      THIS LOOP CALCULATES THE CUMULATIVE PROBABILITIES
                          |
                +-------------+
                + DO          +
   ++++++++++        7         +
   +            + K=1,340     +
   +             +-------------+
   +                      |
   +                      |
   +        ------------------------------------------
   +        | CONTER =0.0                             |
   +        ------------------------------------------
   +                      |
   +                      |
   +             +-------------+
   +            + DO          +
   ++++++++++        2         +
   +            + I=1,KOL     +
   +             +-------------+
   +                      |
   +                      |
   +                      |
 2 +              . *   * .
   +           . *    IF     * .
   +++++++*DBM(I).GE.DELDB(K)  *
   +       * .                . *-------------------------------
   +           * .         . *         T      | CONTER=CONTER+1.0
   +               *  .  *                    ---------------------
   +                  |                            |
   +                  F                            |
   +                  |--------------------------------
   +                  L
```

```
 +                      |
 +          ------------------------------------------
 +          | PROB(K) =CONTER/CKOL                   |
 +          ------------------------------------------
 +                      |
 +                      |
 +                      |
 +                  . *   * .
 +              . *    IF      * .
 +           *     K.EQ.340        *
 +           * .                 . *-------------------
 +              * .           . *        T     | 7    |
 +                  . *   * *                  -------
 +                      |
 +                      F
 +                      |
 +                      |
 +                      |
 +          ------------------------------------------
 +          | DELDB(K+1) =DELDB(K)-0.2               |
 +          ------------------------------------------
 +                      |
 +
 7 ++++++++CONTINUE
      CUMULATIVE PROBABILITIES ARE WRITTEN

       ***WRITE(6,55) (PROB(K),K=1,340)
                      |
                      |
55          FORMAT(8(4X,E11.5))
                      |
            ------------------------------------------
            | ITB(1) =0                              |
            ------------------------------------------
                      |
      CUMULATIVE PROBABILITY VS. POWER IS PLOTTED

            CALL DRAWP(340,DELDB,PROB,ITB,RTB)
            STOP
```

Symbol dictionary:

ALOG10 = external routine

CURENT = magnitude of current at load Z_1 for electric field of 19.4 V/m

CKOL = number of current magnitudes (real number)

DBM = power at Z_1 in units of dBm

DELDB = variable name of increasing value of received power

DRAWP = external routine

ITB = array in subroutine DRAWP containing miscellaneous information for the function to be plotted

KOL = number of current magnitudes (integer number)

POWR = power at load Z_1 in units of watts

POWRM = power at load Z_1 in units of milliwatts

RL = resistive component of load Z_1

RTB = array in subroutine DRAWP containing information for scaling, and producing a title for the completed graph

URENT = magnitude of current at load Z_1 for electric field of 1 V/m

APPENDIX B: EFFECT OF THE MEASUREMENT CABLES ON PICKUP POWER

In determining coupled RF power from incident plane waves to susceptible components of electronic circuits by measurement, the cables between meters and susceptible components also pick up radiated power and cause inaccurate power readings on the meters. In order to observe the effect of measurement cables on RF power absorbed by a susceptible component in an experimental method, the structure model shown in Figure B-1 was analyzed with and without measurement cables. In modeling and calculations, the methods explained in II-A were utilized. Hence the measurement wire pair was modeled as a single wire.

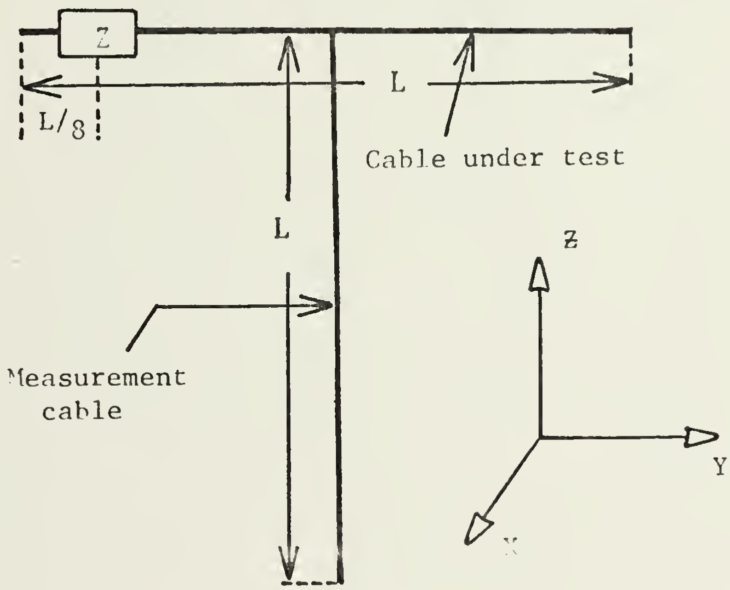

Figure B-1

Model of the test structure and its measurement cables

Coupled power was calculated for ten different azimuth, elevation and polarization angles. The results of these calculations and the parameters of the structure are shown in Table B-1. It is seen that for some aspect and polarization angels the difference in received power for the structure

models with and without measurement cables was appreciable. This difference was large especially for incident plane waves having polarizations parallel to measurement cables. Therefore in MDAC-E's experimental method which was utilized to determine cumulative distribution of RF pickup power, the measurement cables could be a source of error. However, since the calculations were made for unshielded measurement cables in this study, the difference due to shielded measurement cables must be expected to be much less.

Frequency	L	Terminated impedance
3.0GHz	23-5/8 inches	24-j28

POWER CALCULATIONS

θ	∅	η	Power with connection cables (dBm)	Power without connection cables (dBm)	Difference (dBm)
0	30	0	-10.2740	-10.1977	0.0763
45	45	0	-11.2959	-13.5604	2.2645
45	45	45	-7.8373	-8.9120	1.0747
50	240	60	-7.1862	-6.9389	0.2473
20	210	30	-11.7891	-9.6176	2.1715
70	35	10	-10.3597	-11.4176	1.0579
70	35	80	-4.4082	-3.4365	0.9717
65	75	50	-1.8102	-1.7175	0.0927
20	40	40	-9.4609	-8.8612	0.5997
90	0	0	-1.54582	-50.0285	48.4827

Table B-1: Parameters of structure model and calculation record

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